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1. CONSORTIUM EXECUTIVE SUMMARY

During the eighth quarter of the CORD project Stanford University has continued experimental investigation of the CORD testbed. A considerable effort has been put into the characterization of the Contention Resolution Optics (CRO) preprototype, which was received from GTE Laboratories on March 6, 1995. Of primary concern is the instability of the optical signal polarization as it progresses through the CRO. The CRO contains LiNbO₃ optical switches which have switching characteristics dependent on the polarization of the optical signal. Therefore, any drift in polarization has drastic effects on the extinction ratio, or cross-talk, of the switch.

During the seventh quarter and in a more detailed way during the eighth, a series of tests were conducted to pin down the source of the polarization instability. The 100 m single mode fiber delay line, the 50 m polarization maintaining fiber (PMF) delay line and the switches themselves were all sources of polarization instability.

Recently, a demo unit from Hewlett Packard (HP8509B Polarization Analyzer) was received and has allowed to achieve a much better insight into all of these polarization instability phenomena. As for the 100 single-mode delay-line, its polarization instability seems to be of intrinsic nature. It is possible that it could be reduced to some extent by coiling the fiber around a larger-diameter drum, but the procedure holds no guarantee of success. Also performed were numerous experiments with the PMF delay lines and concluded that either the connectors or the v-groove splices were not correctly aligned to the core of the PMF. The only way to correct for this problem was to have the PMF delay lines re-connectorized, which was promptly done. The new results show a 5 to 10 dB extinction ratio improvement, together with a substantially better stability in time.

To compensate for possible polarization shift through the SOAs, installed were additional polarization controllers. This arrangement provides sufficiently stable polarization through the SOAs for many hours of operation without the need for re-adjustment.

Also a better characterization of the polarization and crosstalk behavior of the switches was completed. In particular, both switches exhibited an extinction ratio of only 11 dB presumably because of polarization alignment problems. So the v-groove splices were removed from all ports of the two switches and have all of them re-connectorized. The re-connectorization has been performed so far on one of the two CRO switches, by a company that uses active-alignment procedures. Now, a consistent extinction ratio of 17 dB can be obtained for all switch input-output and switching configurations.

Even though all these attempts at correcting polarization alignment problems were successful, a conclusion was reached that the best way to re-assemble the CRO in such a way that its operation would be high-performance and stable for several hours, was that of pervasively using short spans of polarizing fiber to connect the several different elements of the CRO. This procedure makes the CRO a truly single-polarization device, since the off-alignment power leaking through is fully removed by the polarizing fibers. The great advantage of this approach is that alignment, at all stages of the CRO, is extremely less critical than in the previous setup. This way we will be able to make the CRO reliable enough so that the lookout on the next phase of the project, i.e., final integration of the system, appears promising.

In addition, Stanford University have successfully built and tested a board performing 8-to-64-bit-parallel payload data demultiplexing and have added more features to the control channel

transmitter and receiver modules. Also built and successfully tested were the header recognition hardware and the state machines that optimally configure the CRO switches so that collisions among the incoming packets are minimized.

Due to the substantial progress made in both the optical and logic sections of the system, we are optimistic about the final convergence of all the subsystems into one working system.

During the past quarter the University of Massachusetts group has achieved the following results:

- Developed CRO architectures and control strategies to guarantee FIFO packet reception, i.e. packets in the CRO are received according to their arrival times. Completed the first phase of the evaluation of CRO scalability to a number of wavelengths larger than two, and its scalability to a number of stages larger than two.
- Completed debugging phase of the software modules necessary to emulate reconfigurable optical devices and timed operations of optical devices (e.g., switching time).
- Initiated study phase to implement a user friendly graphical interface for the specification of the optical network layout of the communications system to be simulated with the CONSIP simulator.

CRO Architectures and Control Strategies. Previous results presented in this project were mainly focused on the 2×1 CRO architecture with two stages that exactly fits the current CRO prototype built at GTE. This architecture is capable of resolving receiver contentions in 2 wavelength systems. In the past three months generalization was made to multi-length delay lines to obtain $N \times 1$ CROs capable to deal with a generic number of wavelengths (N) and capable, with their multi-stage design, to arbitrarily reduce the probability of packet loss due to contention below any given value. The resulting CRO structure is also capable of maintaining the order of the arrivals, i.e., packets are received according to the order of their arrival times at the CRO, or in other words, a packet which has reached the CRO cannot be received until all the previously arrived packets are either received or lost due to unresolved contention. Therefore, packets are received according to the well known First In First Out (FIFO) policy.

A bound evaluation of the number of 2×2 photonic switches required to implement the $N \times 1$ CRO with given performance (packet loss probability) was derived. Two alternative CRO architectures were proposed:

- (1) one providing a modular architecture
- (2) one providing a parallel architecture offering limited optical losses and crosstalk.

Software Modules. In the final phase of the optical network simulator development we worked to eliminate remaining problems and inconsistencies in the simulator code. The optical network simulator consists of several program modules. Each of these modules required a specific debugging scheme which would allow to provide a complete evaluation of its specification and simulation mechanisms.

Once a problem/inconsistency was identified, it was addressed and resolved according to its order of importance. Two steps were taken to assure that no design detectable problem has been undiscovered: extensive testing and code inspection. First, tests were designed to determine the functional correctness of the network simulator. Simple optical network architectures have been used as primary objects to be described by the simulator.

These networks were designed in such a way that they would evaluate a particular module/function of the simulator. This allows to narrow down some implementation problems and fix them. After complete evaluation of the functionality of critical software modules the work proceeded with the testing of the overall network simulator. To accomplish this task several combinations of optical devices to form complex network architectures were specified and simulated. The purpose of this second step was to assure the successful integration of all the modules into the same software tool.

The second phase of our debugging process was a walk-through the code. Often a sweep of tests may miss a particular problem that would occur only under very specific circumstances. Also, some design inconsistencies may still be left unnoticed after the above testing phase. Therefore, code inspection allows not only to find design errors, but also potentially to improve the simulator performance.

Graphical Interface. The current release of the optical network simulator tool makes use of a script file that describes the network topology and specifies the functionalities of the optical devices in use. Although such procedure is not complicated it may be time consuming and may require several steps to achieve the complete description of complex optical networks. To make the optical network simulator easy to use even in describing complex communications systems, work has been done on the implementation of the Graphical User Interface (GUI) which will assist the user in entering the necessary information related to the network topology and the description of the optical devices.

At the present time, there is a number of public domain software packages and graphical user interface design languages which utilize X Windows compatible functions and widgets to generate a GUI that operates on UNIX platform. Analysis is in progress of these packages to select the most appropriate one for the realization of our graphical interface. Considerations such as the tool capabilities and the tool complexity will play a significant role in this decision making process.

Currently tools such as Xpip and Tcl/Tk are under evaluation. Both Xpip and Tcl/Tk provide an easy mechanism for GUI design and development. In particular, Xpip makes use of graphical menus for controlling and extending the application under development. Tcl/Tk is a script oriented tool specifically designed for GUI generation. Although more complex than Xpip, Tcl/Tk adds significant capabilities which might be critical in representing and describing optical devices and optical network topologies properly.

In the forthcoming 4 months, we will continue our efforts in testing the existing simulator code by designing and simulating complex optical network architectures. Also, we will develop the graphical user interface for the description and specification of the layout of the optical network under analysis. Finally, integration of this graphical interface module with the existing simulator code will be provided. Original architectures to realize a scalable Nx1 CRO device which takes advantage of the virtually unlimited bandwidth of the fiber composing the delay line (storage device) will be studied and analyzed. The aim of this study is to search for the optimal combination of photonic switches, delay lines and wavelength demultiplexers to build a CRO which guarantees network performance with minimal cost and optical signal degradation.

The following sections contain the technical report of GTE Laboratories only. Stanford University and University of Massachusetts will submit their reports separately.

2. TECHNICAL SUMMARY/DIGITAL OPTICAL SWITCH

The third modification of the original packageable switch design, which included 600 segment curves and 0.05 μm resolution which was discussed last month, did not produce the expected loss reduction in the fabricated curved input and output waveguides. Thus, this quarter's activity shifted from fabricating complete switches utilizing the existing mask set, to solving this loss problem. Two solutions emerged, one focused on the curved waveguides radius of curvature, and the other on the degree of the optical mode's binding to the waveguide.

Previously, all the curved waveguides fabricated had a bend of 7 degrees and a radius of curvature of 2 mm. Thus, a new test mask with the existing 7 degree waveguide bend, but with 6 different radii of curvature (1, 2, 4, 8, 16, 32 mm) was designed and ordered. Using this mask, test wafers were fabricated and loss characterization of the curved waveguides was performed. These measurements provided a quantitative measure of the change in curved waveguide loss as a function of the change in radius of curvature of our weakly bound switchable waveguides. For example: (1) waveguides with a radius of curvature of 8 mm had a measured loss of ~ 5 dB/curve; (2) with a radius of curvature of 16 mm had a measured loss of ~ 3 dB/curve; (3) and with a radius of curvature of 32 mm had a loss of ~ 2 dB/curve. From an extrapolation of these results, it was estimated that curved waveguides with a 50 mm radius of curvature would incur a loss of ~ 1.5 dB/curve. This permitted the selection of a waveguide radius for a low-loss packageable switch mask design.

In addition, new processing procedures and masks were developed to etch additional material away from the cladding layer in a limited region on each side of the curved input and output waveguides to increase the binding of the optical mode to the waveguide and further reduce the loss.

Since the overall geometry of the packageable switch changed with the change in the radius of curvature of the curved input and output waveguides, a month of fabrication time was lost while a completely new packageable mask set was designed and ordered.

To utilize this time profitably, a packageable switch wafer was fabricated utilizing the existing (2 mm radius of curvature) mask set with either the electrodes or polyimide or both omitted from selected switches on the wafer. Characterization of the straight waveguides, Y- and X-switches on this wafer showed essentially the same loss as the previously measured complete switches. This confirmed that the high loss in the switches was due to the small radius of curvature of the waveguides, and not induced by an unknown mechanism in the further processing steps.

In addition, the high-loss (2 mm radius of curvature) curved waveguide sections were cleaved off of the previously fabricated complete (with metal electrodes) old design packageable switches, to permit characterization of the X-switch performance. A blocking configuration (only one input connected to one output at a time) was utilized due to time constraints on the testing set-up. The extinction ratios were found to be limited to ~ 10 dB due to two factors: (1) reflections from the small angle cleaves ($1/4$ degree); (2) and transverse current spreading in the older material wafer used in this fabrication. The first factor pointed out that it is also useful to incorporate low-loss curved waveguides at the input and output ends of a non anti-reflection coated X-switch, to kill reflections from the chip interfaces, as well as facilitate packaging of the device.

The design of the above-mentioned new large radius of curvature packageable mask set (consisting of RIE, nitride, scribe alley, guide, metal, polyimide and blocking masks), with a

50 mm radius of curvature for the curved waveguides, is complete. And all of the mask plates, except the poly and the blocking, have been received from the vendor.

Passive switch test-structures were fabricated on the recently delivered EPI material using this mask set. Preliminary loss characterization of the devices clearly shows that the additional loss of the curved input and output waveguides (at 50 mm radius) is at or below our ability to measure. More detailed measurements are underway to quantify this small loss. In addition another passive switch wafer is in the final stages of fabrication. It is similar to the one just finished except that the curved regions utilize tighter bending waveguides. If this wafer also shows no measurable additional loss due to the curved input and output waveguides, it will confirm the above result. And then both designs are acceptable for fabricating complete packageable switches, once the rest of the masks arrive from the vendor.

For X-switch demonstration purposes, a new set-up consisting of four micro positioning control stages, two for the input fibers and two for the output fibers, is being assembled. The switch electrodes will be connected to external current sources via bonding pads attached to the sample holder. The whole mechanical set up will be mounted on a small hand-portable optical bench.

The remaining 25% of the wafers ordered from EPI products finally arrived. According to the manufacturer's supplied data these wafers meet all our growth specifications.

3. MILESTONES

1. Fabrication of a digital optical switch with extinction ratio >20 dB

Feasibility of low loss curved fanout waveguides have been demonstrated. Fabrication of X and Y switches are underway utilizing the new design.

2. Optimization of switch design for high speed operation.

Delayed till full completion of milestone 1.